

Supervisory ICs empower batteries to take charge

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The care and feeding of rechargeable batteries require that you look at battery chemistry, user application patterns, and protection against failure modes. Supervisory ICs address these challenges, but you still need to consider how to partition responsibility among the battery, supervisory components, and the system microprocessor.

@ a glance

- The charger's basic dc source and supply lines are critical parts of the system.
- Vendors offer a variety of ICs, generally incompatible, that perform many of the charging functions.
- Smart batteries and chargers simplify design and minimize problems.
- Consider how you partition charger-control and supervisory functions.
- Work closely with both the battery vendor and the IC vendor.

Italian physicist Allesandro Volta didn't have to worry about the challenge of recharging battery-cell chemistries when he put together the first electrochemical pile in 1796. After all, his cell chemistry, which was a primary, non-rechargeable cell, was the only one available, and there was no way to recharge it. As a source of electrical potential, it yielded a continuous electrical current, in contrast to the discharging of static electricity stored in capacitors such as Leyden jars or generated by mechanical devices.

You don't have it as easy as Volta did. If you use rechargeable batteries in your system, you have to grapple with a bewildering array of basic battery chemistries, each with its own idiosyncrasies and needs. In addition, you need to consider various charging algorithms and management strategies, supplemented by protection techniques that monitor and guard against battery or system failure. Finally, you have to deal with the reality that system users may do things you wish they wouldn't, such as using a partially recharged battery to replace the weaker one in their system.

As with most power-supply issues, battery charging doesn't normally get the design respect or early attention it deserves. When you design circuits with clock frequencies or bandwidths around 100 MHz, it's easy to think that the "dc" world of batteries is the least of your problems. Although it may be the least of your problems, that doesn't mean it is an insignificant one. You can easily run out of space for the charging circuitry, mismanage the batteries and thus underuse them, or naively expect that users will follow a strict regimen if they are to get the maximum potential from the batteries. Through it all, remember that you can infer the critical internal chemical state of the battery and, thus, its state of charge (SOC), only through indirect characteristics, such as terminal voltage, temperature, and current pumped in vs current drawn out.

In most cases, your first step is choosing the rechargeable-battery chemistry you'll use. Many factors dictate this choice: electrical capacity (C), which is normally defined in ampere-hours; nominal cell voltage; discharge profile; internal resis-

BATTERY-CHARGING ICS

tance and self-discharge; size; cost; weight; ease and speed of recharging; system-usage patterns; battery availability; safety issues; and sometimes even marketing and promotional appeal. Taking these factors into consideration, there are four basic choices to consider: sealed lead acid (SLA), nickel cadmium (NiCd), nickel metal hydride (NiMH), and lithium ion (Li-ion) (see box, "Think back to high-school chemistry"). (Tables 1 and 2, adapted from Reference 1, summarize the performance characteristics of these four chemistries and their fast-charging guidelines.)

The key issue in charging a battery is knowing when to stop charging. Providing the requisite current and voltage sources is more straightforward than knowing when to throttle back these sources, shift from one sourcing mode to the other, and when to stop all charging or go to a trickle mode. You need to consider the dangers of cell overcharging for the chemistry you are using or the consequences of allowing users to switch chemistries, such as from NiCd to Li-ion.

Many parameters and techniques are available for determining battery SOC and end of charge (EOC). You need to use one or more of the following factors as your primary SOC and EOC indicators and others as additional indicators, depending on cell type and application:

- the minimum charge-current threshold plus timer (I_{MIN});
- the terminal voltage vs a threshold, at which point charging current stops or reduces;
- the absolute temperature cutoff (TCO) measured with a thermistor or solid-state sensor;
- the temperature rise above ambient, ΔTCO ;
- the rate of temperature change, $\Delta T/\Delta t$;
- the negative slope of the cell voltage just after peak, $-\Delta V$ (the

TABLE 1—TYPICAL BATTERY-TYPE CHARACTERISTICS¹

Battery characteristics	SLA	NiCd	NiMH	Li-ion
Energy density (Whr/kg)	30	40	60	90
Energy density (Whr/l)	60	100	140	210
Operating cell voltage (V)	2.0	1.2	1.2	3.6 (average)
Discharge profile	Slightly sloping	Flat	Flat	Sloping
No. of recharge cycles ²	500	1000	800	1000
Self-discharge (%/month)	3	15	20	6
Internal resistance	Low	Lowest	Moderate	Highest
Discharge rate (C) ³	<5	<10	<3	<2

¹ These numbers are representative and may differ because of advances in technology and vendor implementations.

² Defined as the battery's achieving 80% of its initial charge capacity on recharge.

³ C=nominal capacity.

TABLE 2—TYPICAL BATTERY-CHARGING CHARACTERISTICS

Fast charge	SLA	NiCd	NiMH	Li-ion
Current C ¹	≥1.5	≥1	≥1	1
Voltage (V/cell)	2.45	1.50	1.50	4.1 or 4.2V±50 mV
Time (hours)	≤1.5	≤3	≤3	2.5
Temperature range (°C)	0 to 30	15 to 40	15 to 40	10 to 40
Primary termination methods	I_{MIN}^2 , ΔTCO^3	dT/dt, $-\Delta V$	Zero dV/dt, $-\Delta V$, slope inflection, ΔTCO^3	I_{MIN}^2 +timer, dT/dt, ΔTCO^3
Secondary termination methods	timer, ΔTCO^3	TCO ³ , timer	TCO ³ , timer	TCO ³ , timer

¹ C=nominal capacity.

² I_{MIN} =minimum current-threshold termination.

³ TCO=absolute temperature cutoff.

decrease in terminal voltage after peak charge);

- the instantaneous rate of change of the cell voltage, dV/dt, including looking for the peak at dV/dt=0;
- the second-time derivative of the cell voltage, d^2V/dt^2 , to detect the charging slope inflection point;
- a timer to track actual charging time;
- and the charge supplied to the battery vs the charge drawn from the battery (called "fuel gauging" or "gas gauging," although "gas" is a dangerous misnomer here).

The reasons for multiple SOC and EOC indications are simple. First, no single parameter unambiguously tells the whole story. Legitimate user actions, such as going from a warm environment to a much colder one, can

fool the EOC circuitry. By using multiple factors, the controller can cross-check and apply various guidelines to better assess the true state of the battery. Second, the time parameter adds to the difficulty of charging and managing batteries. Yet, instantaneous values reveal little about the SOC, so you have to have digital memory or trend and time functions implemented using analog circuitry in your management system.

Most available charging ICs incorporate several of these techniques. Make sure they have the accuracy you need. For example, Li-ion cells require a more precise threshold reading, typically ±50 mV, than do SLA cells. Pay attention to recommendations from the battery vendor you use, because subtle differences are common in

charge and termination requirements between seemingly similar batteries.

Coulomb counting for fuel gauging is the most precise way to assess the cell's status, and many vendors support this technique. Note, though, that counting electrons is never easy, and measurement accuracy depends on many factors, including temperature (Reference 2). Most counters provide compensation for this and other accuracy-limiting factors. Be sure to look at the accuracy of the gauging circuit compared with the dynamic range of your application's draw on the batteries. Applications such as PCs have large variations in current flow; others, such as power tools, tend to draw currents

that may be large in absolute value but that span a smaller range.

Another factor that greatly affects charging time and termination technique is the available charging time. Standard "overnight" charging, meaning 8 to 12 hours, depending on the vendor, gives you time to sense what the battery is doing and to terminate the charge cycle. The penalty for slightly exceeding the optimal charge time is minimal.

Unfortunately, users want fast charging that brings cells to usable charge in less than 1 hour (Reference 3), although some vendors consider cycle times of less than 4 hours a fast charge. The first hour of fast charge typically

brings the cells to 70% of maximum, and the next few hours provide the remaining 30%. Everything, including crossing the overcharge point, happens more quickly in a fast-charge mode, and battery cells are not linear systems. Battery cells react differently when they are charged at the higher rate, and the charging algorithms must take this factor into account.

Several organizations, such as the Bureau for Technology and Innovation (Graz, Austria, US phone 1-860-292-1477) and Advanced Charger Technology (Norcross, GA, 1-770-582-0001) are investigating and implementing various techniques for achieving very fast charge. However, you need to work

THINK BACK TO HIGH-SCHOOL CHEMISTRY

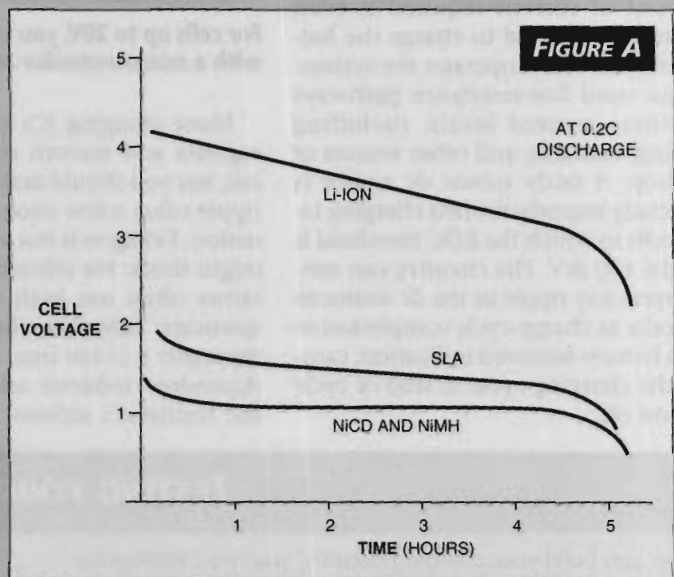
Although Italian physicist Alessandro Volta used a stack of alternating silver and zinc disks with intervening layers of acid-soaked fabric for his battery, your choices are probably sealed-lead-acid (SLA), nickel-cadmium (NiCd), nickel-metal-hydride (NiMH), or lithium-ion (Li-ion) batteries. These four classes constitute most rechargeable cells in use. Each chemistry has its own virtues and vices, as well as unique charging needs and termination techniques.

NiCd cells are charged using a constant current and can be indefinitely trickle-charged at 0.1C without heat buildup. When you fast-charge these cells, you use their rate of temperature rise or peak in cell voltage to indicate it is time to stop charging; some vendors also suggest you look at the absolute rise in temperature compared with the ambient temperature. NiMH cells, like NiCd ones, use a constant current of $\frac{1}{10}C$, but, after 15 to 20 hours, this current must reduce to $\frac{1}{40}C$ or intermittent pulsing. Because NiCd cells have a somewhat flat voltage peak, it's more difficult to determine the point of peak cell voltage to terminate charging.

SLA batteries have a long history, especially in non-portable applications. You can charge them with constant current or voltage or with a combination of current charging and trickle charging with a voltage at the nominal-cell peak value of 2.25V for standby applications.

Li-ion cells offer many power-density, capacity, and nominal-voltage advantages to the system user, but they are the trickiest to charge and manage. A combination of constant current and voltage modes charges Li-ion cells. This chemistry is susceptible to damage from overcharging, excess discharge, and terminal short circuits.

Figure A shows the approximate discharge characteristics of these chemistries at 25°C and at a discharge rate of 0.2C; the curves change considerably at different discharge rates



Each of the four major battery chemistries has a different discharge curve (NiCd and NiMH are similar) at a discharge rate of 0.2C; this feature is one of several factors that affects how you determine the critical end-of-charge point.

and temperatures. The highly sloped curve for Li-ion is a disadvantage in system use but a potential advantage in determining end of charge because a simple voltage measurement tells a lot about cell condition; however, other factors can cloud the reading's reliability.

Note that cells of the same apparent chemistry from different vendors have parameters that differ in key details, so you must check with the vendor and adjust your use and charging accordingly.

BATTERY-CHARGING ICs

closely with your battery vendor to understand what is acceptable and what battery characteristics you can see in such a fast-charge mode.

Although most charging-application literature discusses the charging system's interaction with the batteries, you need to examine your basic dc source for the charging system itself. Even if your system does not draw much current from the batteries, the charging subsystem may need to supply a large current, especially in fast-charge mode. Consider a typical, moderate-capacity, six-AA-cell NiCd pack with 500-mAhr capacity per cell. If you charge this pack in a 1-hour cycle, you need to supply 3A, not including any losses due to charger-circuitry efficiency and cell inefficiency in converting current into chemical energy. The amount of current required is even greater if you have to charge the batteries while a user operates the system.

You need low-resistance pathways for these current levels, including cabling, contacts, and other sources of IR drop. A fairly robust dc source is especially important when charging Li-ion cells in which the EOC threshold is a tight ± 50 mV. The circuitry can misinterpret any ripple in the dc source to the cells as charge-cycle completion or even battery-removed indication, causing the charging cycle to stop or cycle on and off.

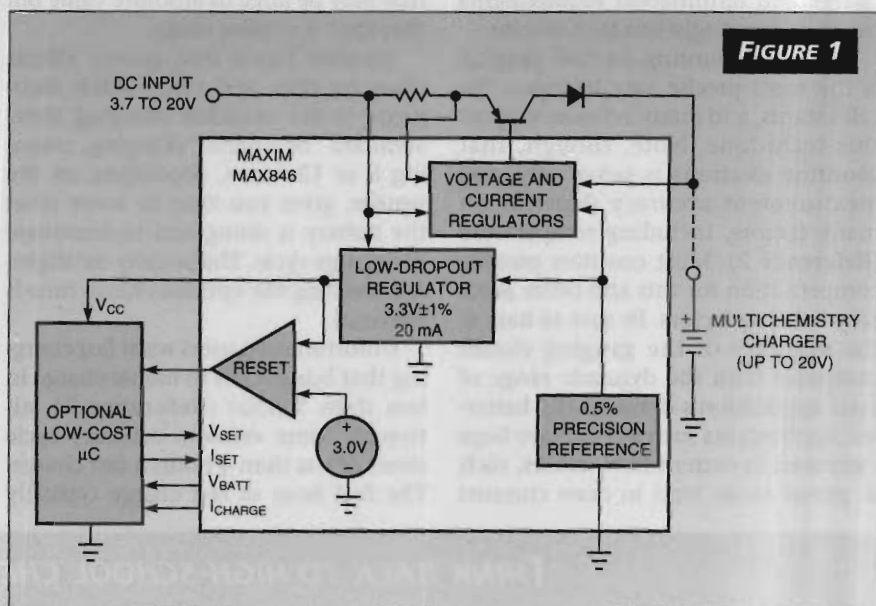


FIGURE 1

For cells up to 20V, you can use Maxim's MAX846 as a stand-alone Li-ion charger or with a microcontroller as the core of a multicell charger.

Many charging ICs are designed to regulate and smooth ripple in the dc rail, but you should make sure the final ripple value is low enough for your situation. Doing so is not as simple as you might think. For efficiency, these regulators often use high switching frequencies; however, the battery cell, especially a Li-ion one, is a frequency-dependent inductor and can hamper the regulator's actions. The combina-

tion of high current and frequencies complicates physical layout as well.

Ideally, the dc source voltage to the charging system would be moderately and consistently higher than the charging voltage to the cells. Unfortunately, this situation isn't always the case, such as when you use a nominal 12V car battery to recharge a large multicell pack. Instead, the source voltage is lower than the voltage needed, so the

TESTING YOUR DESIGN

After you build your charging circuitry, you need some assurance that it works as planned. Because of their unique electrochemical characteristics, batteries are more difficult to test than PLLs, for example. Most users test battery-systems the old-fashioned way: by using actual batteries, operating them under conditions that approximate their applications, and observing the results. You need to run at least 10 cycles on one set of batteries to get meaningful data. You also need to repeat the testing with additional sets of batteries.

The test procedure is time-consuming and labor-intensive. Unfortunately, no short cut exists for comprehensive results. Spice models have limited usefulness beyond first-order approximations. Be sure to test under all the normal operating modes as well as under undesirable but inevitable operating modes, such as fully charged batteries that you place in the charger.

There are some partial options that can increase your testing efficiency, however. You can use a programmable load under software control to replicate some of the operating conditions. This feature can give you some level of confidence, although it cannot replace the battery itself. Also consider building a circuit based on a voltage-regulator design to build a battery simulator, which lets you eliminate the battery for some of your evaluation (**Reference**). Of course, such an electronic circuit cannot provide the cell-temperature rise that your charger may need to indicate SOC and EOC conditions or simulate cell failures.

Reference

"Constant-voltage load box for battery simulation," *Linear Technology Magazine*, August 1996, pg 26.

BATTERY-CHARGING ICs

charger must operate as an efficient boost-mode dc/dc converter.

Even that situation is better than the one in which the source may swing both above *and* below the charging voltage. Again, the car battery, with its wide swings in nominal voltage, typifies this situation. In this case, you need to look at chargers that can provide both buck and boost modes, or you need to preregulate the source voltage before applying it to the charger subsystem.

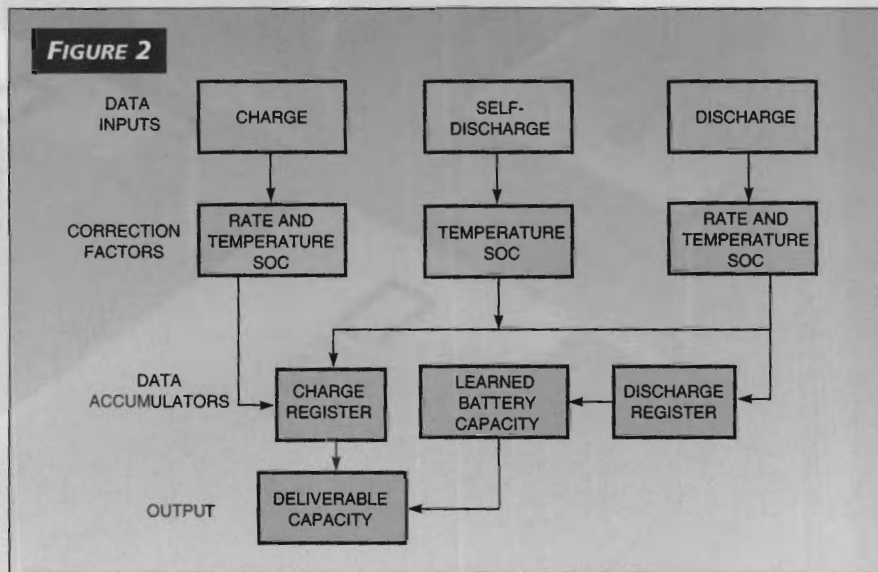
Keep supply efficiency in mind, too. Any heat that the offline supply or the charger dissipates close to the batteries can adversely affect charging SOC/EOC accuracy as well as battery life. Although temperature sensing is part of most charging subsystems, the excess heat pushes you nearer to the battery limits.

"Smarts" change everything

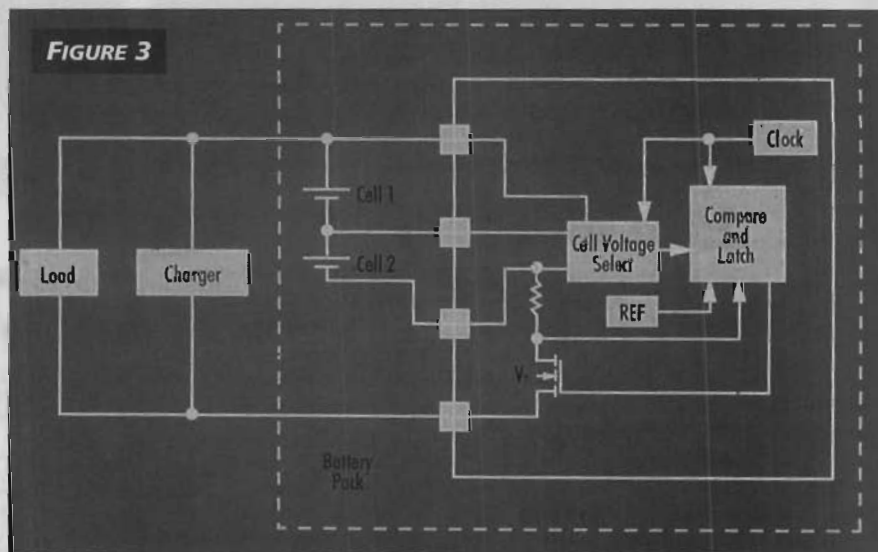
Battery users make charging life difficult. They expect to simultaneously charge and use their systems yet get the same recharge time either way. They take a set of somewhat-recharged batteries from the charger to use in their power tools, replacing it with a more depleted set. They follow erratic usage patterns and go from warm to cold ambient temperatures or vice versa. Typical users treat batteries in advanced technology products, such as cell phones or laptop PCs, as commodities, just as they treat the non-rechargeable cells they use in a flashlight. This behavior is not something you can change.

This treatment confounds optimal battery recharging and complicates your design. In a worst-case example, the charger may monitor current flow into a battery and look for EOC indication. When the user replaces this battery pack, the charging circuitry is in a quandary about the battery's SOC.

Fortunately, the industry realizes that circuitry alone within the charging system cannot solve these problems. Smart chargers and smart batteries provide and use system knowledge about a battery pack (Reference 4). In the smart-charger technique, the battery pack must let the charger know what chemistry it uses and how many



National Semiconductor's LMC6984/LMC6988 battery controller uses a variety of inputs, measurements, and correction factors to determine the battery's true state of charge.



The UCC3911 from Unitrode individually monitors two cells in a Li-ion battery pack; it contains an internal FET for current control.

cells are in the pack. The charger function, which a charger-controller IC and a microcontroller implement, then invokes the appropriate algorithm for that battery pack and keeps track of trends. The smart function can also adapt to user-specific operating habits as well as battery aging with use, based on stored data patterns.

In the smart-battery approach, as

defined by the Smart Battery System specification (SBS), the battery pack is more advanced. It contains the information that the charger needs and directly controls the charger's operation. Circuitry within the battery pack performs fuel gauging; measures voltage, current, and temperature; stores battery-usage and -aging history; protects the battery; and communicates

BATTERY-CHARGING ICs

with the host. The charger does not need to know the battery chemistry or specifics, because the battery pack directs the process. This situation means that the product can use battery types or variations that were unavailable or inappropriate when vendors initially sold the product.

Smart batteries also affect the universal vs single-chemistry charger-IC trade-off. Universal-charger ICs are attractive because they allow you to switch cell types in smart-charger situations, simplify your parts inventory, and use one debugged design across multiple products. In contrast, smart batteries inform you of their status and needs, and you respond with appropriate charging current and voltage with your microcontroller and support circuitry. This approach places a large responsibility on your μ C and puts your firmware in the charging-supervisor-application domain. You may want

a separate μ C dedicated to the charger function, rather than using your system processor.

IC choices can confuse

The good news is that charging management and supervision is well-suited to small-scale mixed-signal ICs, and vendors realize the enormous potential market that such batteries represent (Reference 5). You no longer need individual devices to build current and voltage sources, precision threshold detectors, timers, and sense circuitry. However, the good *and* bad news is that these IC choices embody different architectures and levels of integration.

Although competition among vendors is good in your quest for a well-tailored option, hard-to-compare alternatives require more investigative work on your part. Some vendors offer families of parts that mesh to provide levels

of completeness, and others offer a few optimized or special-function parts. Some ICs are more flexible but require additional external active and passive components than do more limited or specific-function ICs.

For example, Maxim's MAX846A charges Li-ion, NiMH, and NiCd batteries when paired with a microcontroller, delivering charge current through an external pnp transistor or p-channel MOSFET (Figure 1). For low-cost, dedicated applications, you can use the 16-lead QSOP IC as a stand-alone, current-limited, float-voltage source for Li-ion batteries without a μ C. The internal reference is accurate to 0.5%, compatible with the tight specifications of Li-ion cells.

If you expect a source input that swings both above and below the battery voltage, you can use Linear's Technology's 500-kHz LT1512 switching regulator as the core of a charger that

MANUFACTURERS OF BATTERY-CHARGING-RELATED ICs

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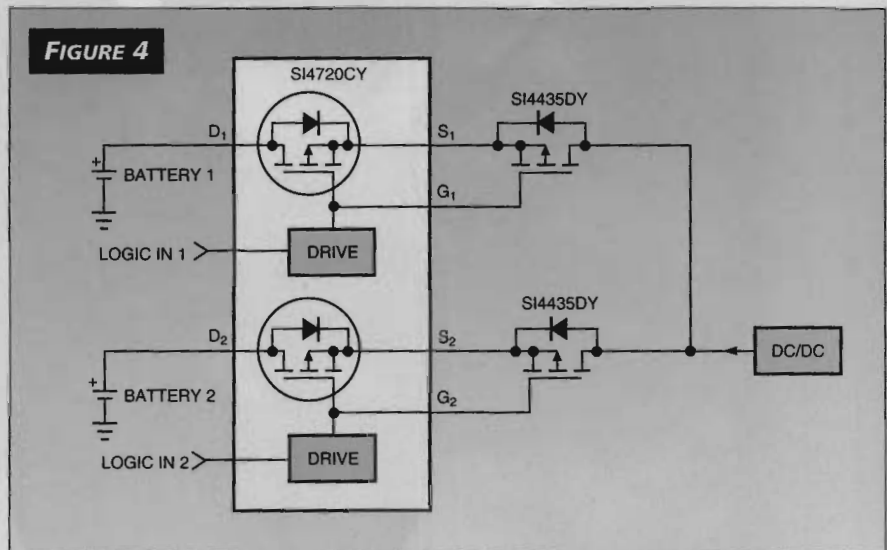
automatically transfers between step-up and -down modes. The current-sense circuit is ground-referred and separate from the battery, which simplifies battery switching and grounding. The eight-pin IC can supply as much as 1A to a Li-ion cell.

For high-level integration, National Semiconductor features the two-IC pair of the LMC6980 battery-data-acquisition system and its companion LMC6984/LMC6988 battery controllers as a universal intelligent charger. The DAS IC includes two 16-bit ADCs to measure temperature, voltage, and current, along with a 128-byte embedded EEPROM for data-storage and look-up-table customization. The controllers, identical except that one is SMBus-compliant, and the other supports single- and two-wire communications, implement three-phase-programmable charging algorithms, as well as capacity monitoring with user-adjustable correction tables to compensate for temperature and other factors (Figure 2).

If fast charging is your challenge, consider Motorola's MC33340 controller, which is designed for 1- to 4-hour charging of NiCd and NiMH cells. It uses negative-slope detection to sense the charge-termination point. To ensure accurate voltage sampling, it momentarily interrupts the relatively high charging current while making that measurement. The eight-pin device also lets you select either programmable time or temperature limits as a secondary charge-termination indicator.

Also for fast charging of NiCd and NiMH cells, the Benchmarq bq2003 prechecks the cell for temperature and voltage faults and supports discharge-before-charge operation to condition the batteries and establish a known baseline. The IC lets you terminate the charge based on rate of temperature change; a decrease in battery voltage after peak; and maximum temperature, time, and voltage. The IC also functions as a switched regulator to control the charging current or gates an external transistor or SCR that controls the current flow.

For NiCd and NiMH batteries, Analog Devices features the ADP3810 and



Temic Semiconductor's Si4720CY dual disconnect switch simplifies switching between battery packs in a multipack design.

ADP3811 charger controllers, respectively. The ADP3810 features preset charge voltages available with levels of 4.2, 8.4, 12.6, and 16.8V, corresponding to one to four Li-ion cells; the ADP3811 lets the user set the final voltage. The controllers are designed to be part of a secondary-side offline controller with optoisolator feedback to the primary side of the PWM circuitry and assume that you have access to a basic microcontroller and an 8-bit ADC to create the charger.

For designers who construct unique charger designs, the TSM101 from SGS-Thomson Microelectronics incorporates a 1.24V series bandgap reference, a current source with on/off control, and two op amps with ORed outputs in an eight-lead package. These blocks allow you to implement a circuit that compares the dc voltage and current level at the output of a switching power supply with the internal reference and provides feedback with an optocoupler to the PWM controller's primary side.

In addition to charging-control ICs, many devices inform you or your system of the status of the battery cells. These devices serve as independent and additional guards in smart batteries or in applications in which the user simply wants to know without complex processor interaction how much charge is in the pack.

Consider the bq2092 from Benchmarq Microelectronics. This fuel-gauge IC provides SOC, capacity-remaining, and time-remaining data, using the SMBus protocol. Meanwhile, the IC directly drives four LEDs to provide a coarse indication of that remaining capacity in 25% increments, which is a good compromise among factors of cost, resolution, and meaningful data to the user.

When you need assurance that the battery is properly charged and ready to provide current, Cherry Semiconductor's CS-2516 pulse-samples the battery pack to verify the terminal voltage under load. Typically, the circuit samples 1 msec every 30 sec by activating an internal load switch that handles as much as 50 mA. If the voltage is below a user-established threshold, the IC allows charging current to flow and can also drive a display indicator.

Multicell/multipack challenge

When you use multiple cells in the battery pack, consider what to measure and what level of knowledge you need about each cell. Cells are not inherently matched devices, although most cell vendors put together packs using cells with close characteristics. Look closely at what your temperature sensor in the pack tells you. Does it indicate the tem-

BATTERY-CHARGING ICs

perature of the cell it is closest to, or does it reflect the average temperature of the entire battery assembly? Ideally, you want to know the temperature of each cell, but learning this information may be impractical. You may need to compensate for thermal differentials in the pack by modifying the charge algorithm.

Yet, individual cells can fail, and you need to adjust your charging accordingly. Pumping more current into a failed or overcharged Li-ion cell can cause drastic problems, such as cell bursting and even explosion. One option is to monitor each cell individually for overcharge, overdischarge, and short-circuit conditions using an IC such as the Temic Si9730. Designed for two-cell Li-ion packs, the device uses its internal ADC to monitor the battery voltage of each cell. If it detects an overcharge on either cell, it bleeds current from that cell at a 15- μ A rate until both cells are at the same terminal voltage and then resumes normal charging.

Unitrode also protects the two-cell pack with its UCC3911 battery protector, which incorporates an internal series-FET switch (Figure 3). Using an internal bandgap reference for comparison, the IC monitors each Li-ion cell's charge status. If it senses overcharge, the FET switch opens to protect the cells and discharge only current flows; in overdischarged state, only charging current can flow. In addition, to conserve power, the UCC3911 enters a sleep mode when it determines that the cells are overdischarged until it senses that the cells are again charging.

If you want to go beyond monitoring to unique serialization and identification, consider the DS2435 Battery ID from Dallas Semiconductor includes 32 bytes of nonvolatile memory that can store data, such as manufacturing-lot code, charging instructions, and warranty information. This feature lets you control the replacement-battery supply for your product and prevents use of unsuitable replacements that may compromise your product's integrity or performance. The IC also includes a direct-to-digital temperature sensor and an elapsed-time counter supported

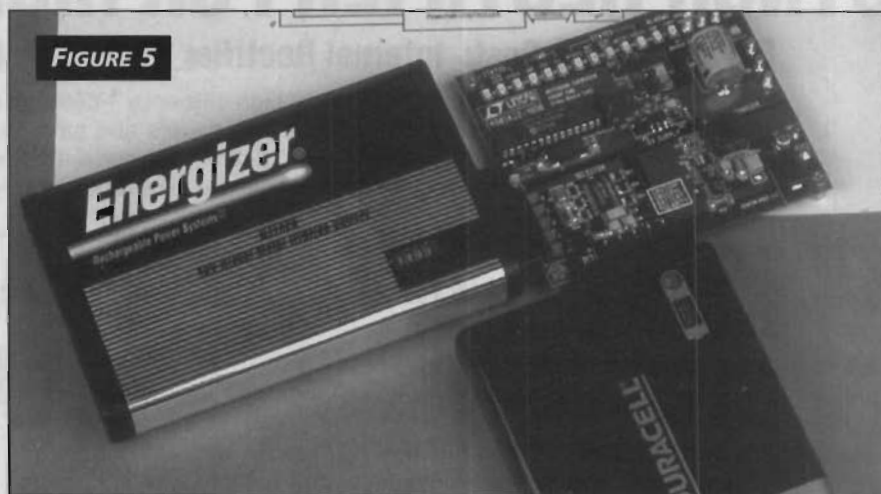


Figure 5
The LTC1479 Powerpath controller from Linear helps simplify managing two battery packs, the charger, and the ac adapter in laptop-PC applications.

by 32 bytes of volatile RAM, so you can perform accurate self-discharge calculations using a time and temperature histogram.

The situation is more complex when you use independent battery packs in the system, such as in some laptop computers, and you need to isolate the packs from each other or from the load when charging. You can use a dual disconnect switch, such as the Si4720CY from Temic Semiconductor, for this application (Figure 4). This IC combines p-channel MOSFETs having 20-m Ω on-resistance with level-shifting circuitry to provide bidirectional blocking and conduction of as much as 6A.

Battery charging, monitoring, and ensuring uninterrupted power in multipack designs can make power-subsystem management complex. At a high level of battery-system control, the LTC1479 Powerpath controller IC from Linear Technology Corp is a switch matrix for laptop computers that manages and arbitrates among the two battery packs, the ac power adapter, the charger, and the backup power system (Figure 5). The IC works with the system power-management controller or processor, directing power from various dc rails to the main system regulators and switching the highest supply to the dc/dc converter when power from any source is interrupted.

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Acknowledgments

Thanks to Dave Heacock of Benchmark Microelectronics, Dale Stoltzka of National Semiconductor Corp, Joe Buxton of Analog Devices Inc, and Roger Chen of Maxim Integrated Products for their comments and insight.

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